Everything You Ever Wanted to Know about Lunar Dust

Larry Taylor
Planetary Geosciences Institute
University of Tennessee
Micrometeorite Impacts on a Lunar Glass Bead

Impact Craters

Projectile $\Phi$ = $\frac{1}{10}$

Crater $\Phi$

5 $\mu$m

Impact Craters

Zap Pits

Courtesy Dave McKay
Lunar Soil Formation

Micrometeorites

Solar Wind

Condensation

Vaporization

Comminution, Agglutination, & Vapor Deposition

The major Weathering and Erosional agent on the Moon is Meteorite / Micrometeorite Impacts
Pieces of minerals, rocklets, and glass welded together by shock-melt glass
### Low-Ti Mare Soils

<table>
<thead>
<tr>
<th>TiO₂</th>
<th>15071-52</th>
<th>15041-94</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12030-14</td>
<td>12001-56</td>
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<thead>
<tr>
<th></th>
<th>Vol.Gl.</th>
<th>Aggl Gl</th>
<th>Px</th>
<th>Plag</th>
<th>Ilm</th>
<th>Olivine</th>
<th>Others</th>
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<tbody>
<tr>
<td>20-45</td>
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</table>

**Volume Abundances in Soil Fraction**

**Glass abundances Increase as Grain-Size Decreases**

### High-Ti Mare Soils

<table>
<thead>
<tr>
<th>TiO₂</th>
<th>71501-35</th>
<th>10084-78</th>
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<tr>
<td></td>
<td>71061-14</td>
<td>70181-47</td>
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</tbody>
</table>
Milky Way of Nanophase Size Metallic Fe\textsuperscript{0}

SEM BSE

all white beads Are metallic Fe\textsuperscript{0}

1 \mu m

Fe\textsuperscript{0}

Agglutinitic Glass

Most Impact Glass Contains Nano-Sized Metallic Fe

Courtesy of Dave McKay
Close-Up of Lunar Soil Particles

Layers of Vapor Deposited NP-Fe

50 nm

Plagioclase

40 nm

Fresh Vapor Deposition

Agglutinitic Glass

Vapor/Sputter Deposited Rims - TEM

Courtesy of Sarah Noble
Thermal Dissociation

Micro-Meteorites

Lunar Soil

Vaporization

Micro-Meteorites

Vapor-Deposition of NP-Fe in SiO2-rich Glass

FeO

SiO2

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Synthesis of Lunar Glass Simulant with NanoPhase Metallic Fe

All Black Dots are Nanophase Fe

Milky Way of np-Fe⁰ SEM

1 µm

call white beads = Fe⁰

TEM Photos

(b) 250 nm

(d) 250 nm

(c) 260 nm

University of Tennessee, Planetary Geosciences Institute
Larry Taylor, lataylor@utk.edu
Concentrations of Solar-Wind Volatile Species in Lunar Regolith Samples, in ppm

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>N</th>
<th>Ne</th>
<th>Ar</th>
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</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>20-100</td>
<td>20-84</td>
<td>96-216</td>
<td>45-110</td>
<td>2-11</td>
<td>1.3-12</td>
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<tr>
<td>Apollo 12</td>
<td>2-106</td>
<td>14-68</td>
<td>23-170</td>
<td>46-140</td>
<td>1.2-6</td>
<td>0.5-4.6</td>
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<tr>
<td>Apollo 14</td>
<td>67-105</td>
<td>5-16</td>
<td>42-225</td>
<td>25-130</td>
<td>0.14-1.6</td>
<td>0.4-2.2</td>
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<tr>
<td>Apollo 15</td>
<td>13-125</td>
<td>5-19</td>
<td>21-186</td>
<td>33-135</td>
<td>0.6-108</td>
<td>0.5-2.7</td>
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<tr>
<td>Apollo 16</td>
<td>4-146</td>
<td>3-36</td>
<td>31-280</td>
<td>4-209</td>
<td>0.4-1.2</td>
<td>0.6-3</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>1-206</td>
<td>13-41</td>
<td>4-200</td>
<td>7-94</td>
<td>1.2-2.7</td>
<td>0.6-2.6</td>
</tr>
</tbody>
</table>

80 wt% of Solar-Wind Particles are in the <50 µm Size Split

Haskin & Warren, 1991
REGOLITH IN PERMANENTLY SHADOWED TERRAIN – PST

40 K imparts brittleness/crushability to soil grains

- Result could be much finer average grain size for soil
- SW abundances are surface property; greatly increased surface areas should increase SW.

**SW retentivity: a function of maximum diurnal T**

- Therefore, retentivity of PST soil should be much greater: +125 °C versus -230 °C

**BOTH TEMP AND FINE-GRAIN SIZE OF SOIL = GREATLY ENHANCED SOLAR-WIND VOLATILES**

2000 ppm Hydrogen, SW or Water, is a “WIN–WIN” Situation
Approximately 50 wt% of Lunar Soil is < 50 \( \mu m \)

\textbf{DUST} = <20 \( \mu m \) = ~20 wt%
Lunar Dust is ~20 wt.% of the average mature Lunar Soil; then 2-5 wt% of that 20 wt% is <1 µm.

That is, the <1 µm portion of the Soil is ~0.5-1 wt%
PSD of Lunar Mare Dust

**Apollo 11 Dust 10084**

Max Particles ~ 100 nm

**Apollo 17 Dust 70051**

Max Particles ~ 200 nm

PSD by SEM
PSD of Lunar Mare Dust and JSC-1Avf

Lunar Dust Simulant, JSC-1Avf, is NOT Suitable for Dust Studies, with regards to PSD

Max in Particles = ~700 nm

Park et al. (2006)
Apollo 17, 70051

Vesicular Dust Grains

Increased reactive surface area

Liu et al. (2006)
Liu et al. (2006) found that Lunar Dust Simulant, JSC-1Avf, may not be suitable for dust studies, with regards to PSD.
**Surface Area**

- SEM image of the particle is assumed to be a slice of 3D particle

\[
\begin{align*}
&\text{3D} & & \text{2D} \\
&\text{Surface area} & \Rightarrow & \text{Perimeter} \\
&\text{Volume} & \Rightarrow & \text{Area}
\end{align*}
\]

- Thus, \( P_v / P_{sp} \) is roughly the factor indicating the surface area increase

\[
\begin{align*}
A_v/A_t &= 0.13 \\
P_v/P_{sp} &= 2.15 \\
\Sigma N_v &= 110
\end{align*}
\]

\[
\begin{align*}
A_v/A_t &= 0.30 \\
P_v/P_{sp} &= 1.88 \\
\Sigma N_v &= 24
\end{align*}
\]

\[
\begin{align*}
A_v/A_t &= 0.18 \\
P_v/P_{sp} &= 3.61 \\
\Sigma N_v &= 154
\end{align*}
\]

\[
\begin{align*}
A_v/A_t &= 0.25 \\
P_v/P_{sp} &= 4.6 \\
\Sigma N_v &= 145
\end{align*}
\]

\[
\begin{align*}
A_v/A_t &= 0.26 \\
P_v/P_{sp} &= 2.23 \\
\Sigma N_v &= 39
\end{align*}
\]

- Av = total area of vesicles; 
- At = total area of particles; 
- \( P_v \) = total perimeter (vesicle-bearing particle); 
- \( P_{sp} \) = the perimeter (vesicle-free particle); 
- \( \Sigma N_v \) = the total number of vesicles.

Reaction Surface Areas are several times larger than external area alone

Park et al. (2006)
Compare to Simulant JSC-1Avf

Dust Simulant JSC-1Avf approximates Lunar Dust
Bulk Chemistry and \( ^{169}I_s/FeO \) Values of the <10 \( \mu \)m Fractions of Lunar Mare Soils

<table>
<thead>
<tr>
<th>Soil # Maturity</th>
<th>10084 78</th>
<th>12030 14</th>
<th>12001 56</th>
<th>15071 52</th>
<th>15041 94</th>
<th>71061 14</th>
<th>71501 35</th>
<th>70181 47</th>
<th>79221 81</th>
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<tbody>
<tr>
<td>SiO(_2)</td>
<td>42.1</td>
<td>46.2</td>
<td>46.0</td>
<td>46.9</td>
<td>46.6</td>
<td>40.2</td>
<td>40.4</td>
<td>41.5</td>
<td>42.3</td>
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<tr>
<td>TiO(_2)</td>
<td>7.25</td>
<td>3.01</td>
<td>2.78</td>
<td>1.57</td>
<td>1.79</td>
<td>7.89</td>
<td>8.27</td>
<td>6.54</td>
<td>5.83</td>
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<tr>
<td>Al(_2)O(_3)</td>
<td>16.9</td>
<td>13.9</td>
<td>14.9</td>
<td>17.1</td>
<td>16.4</td>
<td>13.8</td>
<td>14.5</td>
<td>15.4</td>
<td>15.9</td>
</tr>
<tr>
<td>Cr(_2)O(_3)</td>
<td>0.27</td>
<td>0.43</td>
<td>0.42</td>
<td>0.40</td>
<td>0.37</td>
<td>0.44</td>
<td>0.40</td>
<td>0.39</td>
<td>0.35</td>
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<tr>
<td>CaO</td>
<td>12.3</td>
<td>10.4</td>
<td>11.2</td>
<td>11.8</td>
<td>11.6</td>
<td>10.7</td>
<td>11.2</td>
<td>11.5</td>
<td>11.7</td>
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<tr>
<td>MnO</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.15</td>
<td>0.17</td>
<td>0.20</td>
<td>0.19</td>
<td>0.18</td>
<td>0.17</td>
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<tr>
<td>FeO</td>
<td>12.0</td>
<td>14.3</td>
<td>12.5</td>
<td>9.59</td>
<td>11.0</td>
<td>14.8</td>
<td>13.5</td>
<td>12.7</td>
<td>11.3</td>
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<tr>
<td>Na(_2)O</td>
<td>0.46</td>
<td>0.53</td>
<td>0.51</td>
<td>0.48</td>
<td>0.49</td>
<td>0.46</td>
<td>0.42</td>
<td>0.46</td>
<td>0.49</td>
</tr>
<tr>
<td>K(_2)O</td>
<td>0.15</td>
<td>0.35</td>
<td>0.30</td>
<td>0.22</td>
<td>0.23</td>
<td>0.11</td>
<td>0.11</td>
<td>0.13</td>
<td>0.15</td>
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<tr>
<td>P(_2)O(_5)</td>
<td>0.20</td>
<td>0.32</td>
<td>0.24</td>
<td>0.09</td>
<td>0.20</td>
<td>0.05</td>
<td>0.06</td>
<td>0.10</td>
<td>0.07</td>
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<tr>
<td>SO(_2)</td>
<td>0.14</td>
<td>0.15</td>
<td>0.29</td>
<td>0.14</td>
<td>0.11</td>
<td>0.25</td>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>98.16</td>
<td>98.14</td>
<td>98.12</td>
<td>98.30</td>
<td>98.35</td>
<td>98.19</td>
<td>98.11</td>
<td>98.16</td>
<td>98.10</td>
</tr>
<tr>
<td>( ^{169}I_s/FeO )</td>
<td>145</td>
<td>32</td>
<td>115</td>
<td>159</td>
<td>161</td>
<td>28</td>
<td>88</td>
<td>104</td>
<td>169</td>
</tr>
</tbody>
</table>

LUNAR SOIL CHARACTERIZATION CONSORTIUM; Taylor et al (2001)
Table 4. Average Compositions of Agglutinitic Glasses in the Nine Mare Soils.

<table>
<thead>
<tr>
<th></th>
<th>10084 -78</th>
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<tr>
<td></td>
<td>20-45 µm</td>
<td>10-20 µm</td>
<td>&lt;10 µm</td>
<td>20-45 µm</td>
<td>10-20 µm</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>44.5 (44)</td>
<td>45.2 (42)</td>
<td>44.5</td>
<td>47.8 (46)</td>
<td>47.9 (53)</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>2.96 (226)</td>
<td>2.94 (182)</td>
<td>3.30</td>
<td>2.74 (240)</td>
<td>2.53 (190)</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>17.4 (75)</td>
<td>18.0 (80)</td>
<td>16.4</td>
<td>13.3 (59)</td>
<td>12.9 (62)</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.31 (19)</td>
<td>0.24 (18)</td>
<td>0.24</td>
<td>0.32 (31)</td>
<td>0.36 (28)</td>
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<tr>
<td>MgO</td>
<td>8.69 (325)</td>
<td>8.45 (335)</td>
<td>8.68</td>
<td>8.73 (375)</td>
<td>8.81 (317)</td>
</tr>
<tr>
<td>CaO</td>
<td>13.2 (25)</td>
<td>13.9 (26)</td>
<td>13.2</td>
<td>11.6 (29)</td>
<td>11.7 (22)</td>
</tr>
<tr>
<td>FeO</td>
<td>10.6 (53)</td>
<td>10.2 (53)</td>
<td>11.8</td>
<td>13.7 (51)</td>
<td>13.5 (47)</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.36 (13)</td>
<td>0.36 (25)</td>
<td>0.33</td>
<td>0.46 (27)</td>
<td>0.48 (29)</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.09 (7)</td>
<td>0.11 (7)</td>
<td>0.12</td>
<td>0.31 (24)</td>
<td>0.29 (22)</td>
</tr>
<tr>
<td>Total</td>
<td>98.11</td>
<td>99.35</td>
<td>98.49</td>
<td>98.82</td>
<td>98.47</td>
</tr>
</tbody>
</table>
Vapor-Deposited Nanophase Fe° on Plagioclase

TEM: (all black spots = np-Fe)

NP-Fe° Imparts Magnetic Susceptability to Normally Diamagnetic Feldspar

SiO₂-rich glass

Plagioclase

Use Magnets?

Lunar Dust Can be Attracted to a Simple Magnet

Wentworth et al. (1999)
Apollo 11 10084: <45 µm
Lunar Soil MAgnetic Collector (LSMAC)
Microwave Heating of Lunar Soil

NanoPhase $\text{Fe}^0$ in Silicate Glass

Lunar soil in your kitchen microwave oven will melt [$\sim$1200 °C], BEFORE your tea-water boils [100 °C]!!

(Taylor and Meek, 2005, Jour. Aerospace Engr.)
Lunar Dust Effects are a Major Problem;

Dust (<20 µm) = ~20 wt% of Mature Lunar Soil;

About 1 wt% of Mature Soil is < 1 µm;

PSD of Mature Lunar Soil Peaks at ~100-200 nm;

Impact Glass (with np-Fe) of < 1µm Dust = ~80 %;

Dust Particle Morphologies are Unusual;

Unique Properties of Soil are from Nanophase Fe: Magnetic Attraction; Microwave Coupling.